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The value of critical destruction: Evaluating multispectral image processing methods for the analysis of primary historical texts

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Abstract

Multispectral imaging—a method for acquiring image data over a series of wave-
lengths across the light spectrum—is becoming a valuable tool within the cultural

and heritage sector for the recovery and enhancement of information contained within primary historical texts. However, most applications of this technique, to date, have been bespoke: analysing particular documents of historic importance. There has been little prior work done on evaluating this technique in a structured fashion, to provide recommendations on how best to capture and process images when working with damaged and abraded textual material. This article introduces a new approach for evaluating the efficacy of image processing algorithms in recovering information from multispectral images of deteriorated primary historical texts. We present a series of experiments that deliberately degrade samples cut from a real historical document to provide a set of images acquired *before* and *after* damage. These images then allow us to compare, both objectively and quantitatively, the effectiveness of multispectral imaging and image processing for recovering information from damaged text. We develop a methodological framework for the continuing study of the techniques involved in the analysis and processing of multispectral images of primary historical texts, and a dataset which will be of use to others interested in advanced digitisation techniques within the cultural heritage sector.

1 Introduction

Multispectral imaging is an advanced digitisation method for acquiring image data over a series of wavelengths across the light spectrum. Combined with image processing, it has become a valuable tool for the enhancement and recovery of information contained within culturally important documents, providing a means, in some cases, to recover lost text, or examine other features no longer detectable by the human eye. However, applications of multispectral imaging within the cultural and heritage sector have mainly been bespoke, with limited access to or understanding of the techniques and methods used to recover damaged text. The barriers to accessing this technology will become lower as the equipment becomes commercially available; however, it is important that we better understand the methods and approaches used for multispectral imaging in order to be able to use such techniques efficiently, whilst maximising the information we can recover from cultural objects.

This article describes a highly interdisciplinary approach to evaluating multispectral imaging and image processing in the context of primary historical sources. We introduce a formal methodology to evaluate image processing of multispectral data and

provide a framework for developing new, best practice methods when using multispectral processes to image damaged texts. We do so by first building up a large dataset of multispectral images of actual parchment, taken *before* and *after* a set of degradation procedures that were designed to match the most likely types of damage which may occur over the lifetime of parchment documents. This dataset then allows us to evaluate the efficacy of image processing algorithms attempting to recover damaged text, and to make recommendations on how best to apply multispectral imaging when attempting to recover information from damaged text. Our novel approach, which requires the necessary, controlled destruction of a historical parchment document, presents a formal methodology in acquiring, processing, and analysing multispectral data. It also led to the creation of a large dataset consisting of a series of multispectral images showing both the initial and degraded state of samples from a real manuscript, providing a valuable tool for the advanced digitisation research community. As such, this article makes a major contribution to our understanding of how multispectral imaging can be used across the cultural and heritage sector, and demonstrates how an interdisciplinary approach centred on questions raised from within a Digital Humanities project can advance our

understanding of image processing for both the cultural heritage and engineering science sectors.

2 The Digital Humanities and Imaging

Although most effort in the Digital Humanities is focussed on the production, analysis, and visualisation of text¹, there is a recent and growing interest in the community towards digital imaging, and how image capture and processing techniques can aid us in uncovering new bodies of information, particularly from historical documents². Digital imaging technology has been used to produce detailed and trustworthy surrogates of historical documents for decades (Deegan and Tanner, 2002; Hughes, 2004; Terras, 2008), and digitized versions of primary historical sources are often adequate for the needs of most scholars. However, improvements in image processing and analysis have led to a number of exciting and important digital humanities projects which can reveal a greater wealth of information about the originals, beyond traditional digitisation technologies. Leveraged by technological improvements in image acquisition and image processing, humanities scholars have been able to image, analyse, and recover more information from historical texts (Chabries *et al.*, 2003; Terras, 2006a; Salerno *et al.*, 2007; Tanner and Bearman, 2009). One of the most promising techniques³ is multispectral imaging, which can provide additional evidence of the content of a document when it is difficult to read with the naked eye, when further information about the physical composition of a document and ink identification is required (Senvaitenė *et al.*, 2005), or when information is required about its provenance (Tanner and Bearman 2009).

3 Multispectral Imaging

Light is an electromagnetic wave, often characterised by its wavelength (which we perceive as colour), which is the distance between two consecutive peaks of the wave. The spectrum that is visible to humans includes wavelengths from approximately

380 nm to 760 nm (Fig. 1). Light with a wavelength longer than 760 nm is referred to as infrared; ultra-violet is light with wavelengths shorter than 380 nm (Peatross and Ware, 2013). Most digital imaging equipment captures the same broad spectra of light that is visible to humans with a combination of broadband red, green, and blue sensors (this is hardly surprising, given that the outputs of most imaging technologies are those which humans should be able to see). In contrast, multispectral imaging measures a series of discrete wavelengths over a defined range. These images can be acquired in the visible spectrum and also in the infrared and ultra-violet spectrum (with images that include a broader range of wavelengths often being referred to as hyper-spectral (Landgrebe, 1999)).

Multispectral images are reasonably straightforward to acquire if appropriate light sources and detectors are available along with a method for wavelength selection. A spectrum of light is usually selected through the use of filters, or via a light source⁴. For example, a series of filters placed in front of a camera lens can allow images to be captured in distinct wavebands (Hardeberg *et al.*, 2002; Attas, 2004; Rapantzikos and Balas, 2005) or, in a more recent development, light sources can be used which emit at specific wavelengths (Easton *et al.*, 2010; Marengo *et al.*, 2011; Hollaus *et al.*, 2013). Images may then be acquired using a commercial camera or a more sophisticated scanning system. The resulting sets of images can show different aspects of a document at different wavelengths (Fig. 2).

Multispectral imaging was first developed by NASA in the 1950s to determine the composition of objects in space (Landgrebe, 1999) and more recently has been used in medical imaging, for example in imaging the interior of the eye (Everdell *et al.*, 2009). It is also incredibly useful to help in reading documents: given that different inks have different spectral signatures due to their differing chemical composition, multispectral imaging can be used to differentiate inks used in different areas on a document, different depths within a document (such as in the case of palimpsests) or to differentiate ink from other types of document damage, such as mould or abrasion. In the cultural

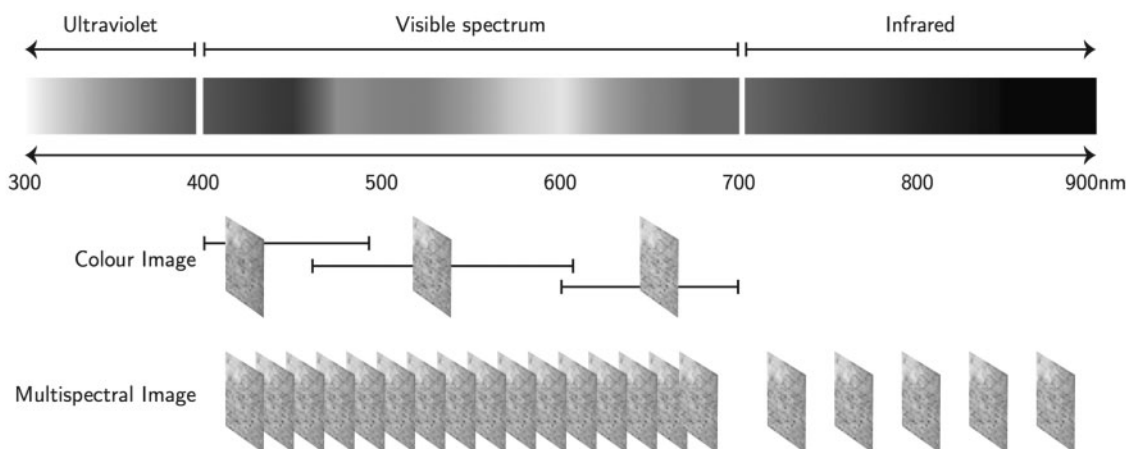


Fig. 1 Multispectral images are captured in a similar process to colour images, but with many images captured at discrete narrow ranges of the light spectrum, rather than a small number of images which are each sensitive to light at a broader range of wavelengths¹⁹

and heritage sectors, multispectral imaging has been used across a range of documents including the Archimedes Palimpsest (Salerno *et al.*, 2007), the Dead Sea Scrolls (Chabries *et al.*, 2003; Tanner and Bearman, 2009), carbonised scrolls from Herculaneum (Chabries *et al.*, 2003), letters from the Hudson Bay Archives (Goltz *et al.*, 2007), palimpsests from the Saint Catherine Monastery in Egypt (Easton *et al.*, 2010), improving tarnished daguerreotypes (Goltz and Hill, 2012), removing effects of ink-bleeding, ink-corrosion, and foxing (Joo Kim *et al.*, 2011), and recovering the diaries of David Livingstone (Knox *et al.*, 2011). Although multispectral imaging is currently the leading technique for recovering lost text in historical manuscripts, there are no guidelines which determine when it is the most appropriate technique compared to imaging at a single wavelength, or what the best wavelengths to use are. One purpose of this work is to establish a means to compare different imaging approaches objectively so that such guidelines can be evidence-based.

Most of the reported applications of this technique in the cultural and heritage sector are to specific documents of great historical importance. Wider use of the technology is now inevitable as more examples of successful recovery from multispectral images of historical documents arise,

although a careful cost–benefit analysis is required to consider the type of data that a multispectral imaging project might yield, given the present (but falling) costs of undertaking this kind of imaging. As the availability of the technique is expected to increase, it is important to consider best practice⁵ in capturing and processing multispectral images. Questions remain as to how best to take advantage of digital visualisation technology to present multispectral image data of cultural heritage to historians and palaeographers (Bonanni *et al.*, 2009, Ponto *et al.*, 2009). In addition, there is little evidence available about how best to process or analyse multispectral images (Giacometti, 2013). Further processing (the computational manipulation of digital images, see Gonzalez and Woods (1993) for an introduction) of multispectral images can allow important historical features and details to be identified, enhanced, and separated from other features, and it is important to understand what image processing approaches are most useful when dealing specifically with multispectral images of particular types of damage found on primary historical texts. Additionally, multispectral imaging can be misunderstood, with the technology sometimes being described as if it were magic (for example, see Zolfaghariard, 2014), and there is a need for a systematic investigation into the effectiveness and

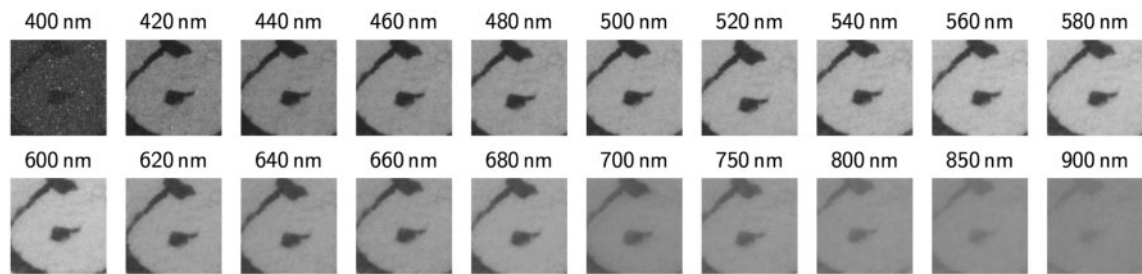


Fig. 2 Multispectral detail of a single feature from our sample 0602R captured using a monochrome camera. Note the variation in intensity and contrast of the writing and ink across the imaged wavelengths. It can be observed how, initially, the ink gains contrast slightly, with a darker background in the shorter wavelengths. Around the longer wavelengths in the visible spectrum and into the near-infrared, the contrast suddenly drops quite significantly, rendering the contrast in the 900 nm image almost null

usefulness of the technique for the cultural and heritage sector.

Previous multispectral imaging capture projects, applied to specific examples of texts of historical importance, have concentrated on recording documents in their current state (generally once important features are illegible). Here, we investigate best practice in the multispectral imaging of heritage material by imaging a parchment document *before* and *after* a series of degradation processes, allowing us to assess the effectiveness of image processing algorithms to recover information from degraded documents. This gives us a unique platform for evaluating the quality of recovered images, and allows us to assess the performance of image processing algorithms for analysis of these images. We propose a method for objectively comparing images of degraded documents, and develop a method for indicating which image processing methods are most appropriate for recovering text which has suffered from specific types of damage. In addition, at a time when ‘critical making’⁶ is being much discussed in the Digital Humanities, we propose that our approach to ‘critical destruction’ demonstrates the importance of adopting quantitative approaches when undertaking Digital Humanities research.

4 Method

The evaluation of image quality and the performance of methods which produce images of cultural

heritage documents is a complex and challenging task (MacDonald and Jacobsen, 2006), and there has been little attempt to evaluate multispectral image quality previously. Partly this is because ‘quality’ is ill-defined. Here, we are able to introduce a new, objective definition of ‘quality’, namely, the amount of shared information between an image of the undamaged parchment and one of the recovered text. This is explored more fully in section 4.4. Existing multispectral image data are often particular to an individual document, and the success or failure of analysis is determined by the subjectively perceived legibility of the writing (Easton *et al*, 2003; Attas, 2004; Knox, 2008). In order to assess multispectral image processing methods objectively, it is necessary to acquire data under controlled conditions: capturing multispectral images of a manuscript *before* any degradation occurs, and then capturing images of the manuscript *after* degradation. These two sets of images enable evaluation of the image processing methods and their performance on a real degraded document⁷. Naturally, this is impossible to do with historical text which has already been degraded (and no curator would allow us to degrade a primary historical text of any importance), but it is possible to adopt an experimental approach in which a real manuscript is deliberately degraded in a rigorously controlled fashion, and its corresponding deterioration documented via multispectral imaging. This allows us to quantitatively and objectively compare the recovery of text from the degraded manuscript and to

evaluate the success of multispectral imaging and its related processing approaches when faced with specific documentary damage.

Such an experimental approach is common in the field of conservation: the changes that parchment (or more specifically, its collagen fibres) undergo have been studied when subjecting samples to heat (Chahine, 2000), ultraviolet light (Meghea *et al.*, 2004) even open flame (Giurginca *et al.*, 2009) and chemical solutions (Dobrusina and Visotskite, 1994). Other methods, such as optical coherence tomography (Góra *et al.*, 2006), x-ray fluorescence, optical fluorescence (Dolgin *et al.*, 2007), and x-ray diffraction (Kennedy and Wess, 2006), have been used to identify the state of degradation of parchment: however, ours is the first known study to focus on the macroscopic effects of degradation agents on the legibility of primary historical texts in order to understand how we can most effectively use multispectral methods.

4.1 Degraded and degrading text

We chose to focus on parchment documents for our study, given that parchment remains the primary medium of large quantities of culturally important documents in archives, museums, libraries, and private collections. A durable, stiff material, parchment is made of animal skin and consists of structured collagen fibres, but is highly sensitive to changes in humidity, and is endangered by biological, thermochemical, and mechanical damage (Reed, 1972; Clarkson, 1992; Larsen, 2007). Through consultation with conservators and archivists, we identified twenty methods of degradation that commonly affect historical parchment material, changing its physical characteristics at both microscopic and macroscopic levels (Vnouček, 2007). These included both physical and chemical agents to mimic the kinds of damage that parchment documents can be expected to incur during their lives, from technological mistakes during production, to improper use, unsuitable storage conditions, disasters, and natural ageing (Table 1). The damage agents were selected so as to affect not only the properties of the parchment, but also the legibility of text in various ways, for example, shrinking or otherwise deforming the parchment, and obscuring or effacing the

writing via physical, chemical, or biological reactions and stains (Giacometti *et al.*, 2012).

4.2 The parchment prepared

An eighteenth-century manuscript was donated for our experiment from London Metropolitan Archives⁸. The document was an assignment of property which had been deemed to hold no historical or scholarly value, and had been de-accessioned from their collection prior to our request for parchment material in accordance with The National Archives guidance on deaccessioning and disposal (The National Archives, 2015). The manuscript was written in iron gall ink on prepared animal skin, measured approximately 70 × 70 cm, and was composed of two large leaves (Fig. 3), which were folded in thirds both horizontally and vertically. Both leaves had red margin guidelines and a blue seal glued outside the left margin. The outer leaf contained a large stamp on the top left corner and a fold trapping the inner leaf with red wax. Both leaves had writing on the recto covering most of the area of the leaf enclosed by the red margin. The outer leaf had a written section on its verso, detailing the date and contents of the document. The recto of the manuscript corresponded with the flesh side of the parchment, the verso with the hair side. Apart from some signs of wear and tear, especially around the folds of the text, it was in overall good condition. Twenty-three 8 × 8 cm flat square sections were cut from the parchment as samples for this research: each sample contains written text.

Each of the 23 samples was selected from a flat area of the manuscript, where the writing covered the surface of the recto (flesh side), and the verso was empty and without blemishes. Folds and marks of any kind were avoided. There were three exceptions: two of the samples were cut so as to contain writing on both the recto and verso, and one sample was cut from a folded area. The old fold sample and one of the samples with writing on both sides were kept as controls. The samples were imaged, then a series of treatments were applied to damage the twenty samples, as described in Table 1; three were left untreated and kept intact as controls (giving a total of 23 samples). The samples were then

Table 1 Summary of different types of degradation (in small capitals), giving the reason for the degradation, the circumstances in which it might occur, and the type of degradation

Degradation reason		Circumstances	Mechanical damage	Chemical, biological, or environmental damage	Damage by extraneous substances
Technological mistakes	During manufacture	Lime solution, acidity, finishing	Scraping	Hydrochloric Acid, Calcium Hydroxide Sulphuric Acid	Oil
	During writing During binding	Ink acidity Unsympathetic binding	Mechanical Damage		
Storage	Environmental changes	Temperature, humidity		Mechanical Damage	Heat, Desiccant, Mould
	Exposure to light	Visible light, UV	UV Light, Controls		
	Pollutants, dirt	Chemical reactions	Smoke, Sulphuric Acid, Controls		
	Natural disasters	Fire, smoke, water	Heat, Smoke, Water		
	Biodegradation	Micro-organisms, insects, rodents		MOULD	
	Mechanical destruction	Rubbing, folding	Mechanical Damage		
Use	Erasures, changes to text	Corrections, re-usage	Scraping		
	Mishandling, misuse		Mechanical Damage, Scrunching		
	Accidents	Spillage		Blood, Red Wine, Black Tea, Iron Gall Ink, Water	Blood, Oil, Red Wine, Black Tea, Aniline Dye, Iron Gall Ink, Indian ink
	Repairs	Historical, conservation treatments		Water, Sodium Hypochlorite	
	Rebinding	Unsympathetic binding	Mechanical Damage		
	Palaeographical and conservation experiments	Palimpsest text recovery, bleaching		Hydrochloric Acid	Oil
	Reformatting, digitisation		Mechanical Damage	UV Light	
Natural ageing				Controls	

In the table are also highlighted the kinds of degradation that naturally occurred to the manuscript during our experiments; these are identified by the keyword *Controls*.

reimaged, producing image sets acquired before and after damage.

4.3 The parchment imaged

Multispectral images were acquired of every sample on two separate sessions in order to capture the samples in an untreated and treated state. The imaging station and equipment were not moved between sessions. Each sample was imaged under

three modalities which represent different ways of illuminating and capturing the images (MacDonald *et al.*, 2013). The Nikon camera is a consumer camera which has a high pixel resolution and acquires colour images; the monochrome camera is a scientific camera which acquires greyscale images only (making it more convenient for multispectral imaging though a filter) and has increased sensitivity to the infrared, but has a lower pixel

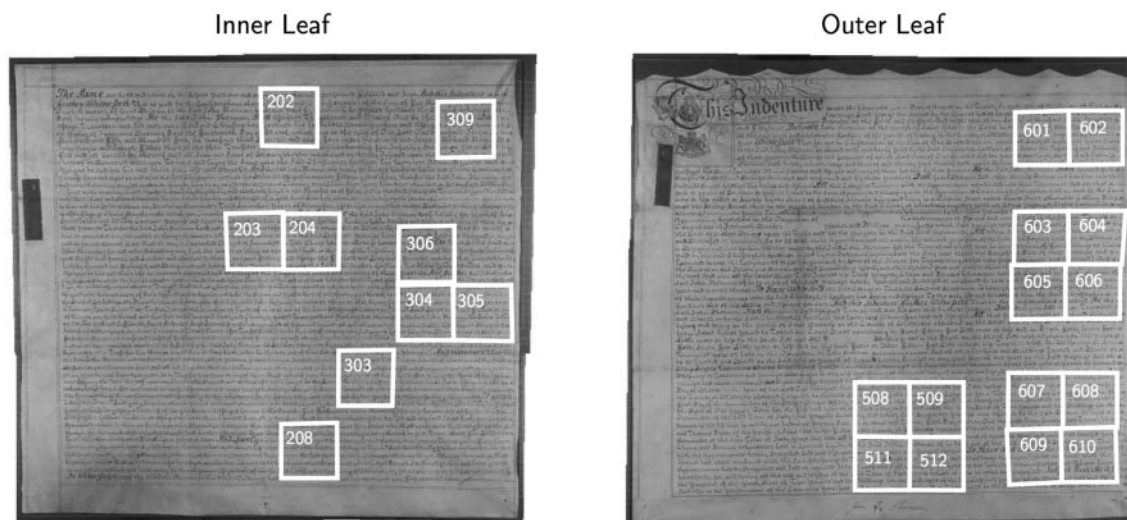


Fig. 3 A diagram of the location of the samples cut from both leaves of the iron gall ink on parchment manuscript. Each sample is 8 cm square, giving an overall impression of the size of the original parchment

resolution. Using both reflective and transmission imaging allowed both surface and deeper features to be detected.

(1) Colour reflective imaging. This maximises sensitivity to surface features on the parchment. A Nikon D200 camera was mounted on a copy-stand with white tungsten-halogen incandescent lighting set at 45° (these emit from 400 to 1,000 nm, with peak power from 500–750 nm; see Fig. 4). Sixteen bandpass filters with centre wavelengths 400–700 nm and bandwidth 20 nm (Unaxis Optics, USA) were fixed in turn to the front of the camera lens. The camera was fitted with a Nikkor 105 mm f2.8 macro lens and set to an aperture of f8 throughout.

(2) Colour transmission imaging. This used the same camera, but the light source was a light-box beneath the parchment, ensuring that only light which had passed through the parchment was detected, thereby increasing sensitivity to deeper regions of the parchment, and avoiding specular reflections. Its fluorescent lamps had a narrower bandwidth and did not provide measurable power above 800 nm (which did not affect the colour imaging, because our longest wavelength filter was 700 nm). The same sixteen bandpass filters and the same camera lens were

used. We also imaged each sample with no filter, giving 17 captures per sample.

(3) Monochromatic reflective. In order to detect light in the near infrared, we used a monochrome camera (Kodak Megaplug 1.6i) which did not have an infrared cutoff filter. This enabled us to investigate longer wavelengths using five additional infrared bandpass filters from 750–950 nm, centred every 50 nm. This camera has a lower spatial resolution than the Nikon (1,534 × 1,024 pixels compared to 3,872 × 2,592 pixels) and a lower bit depth (12 bits compared to 16 bits). The lens was a Nikkor 50 mm f2, which was set at a constant aperture of f/5.6 for all images. The sampling resolution on the surface of the parchment was approximately 12 pixels/mm (300 dpi).

A total of 2,800 images were acquired in two imaging sessions, requiring careful data management processes to name each sample and record metadata about the process (Table 2; Giacometti, 2013).

4.4 Image processing

The analysis of images created by our experimental approach is important in several ways, as we can use various image processing algorithms to produce



Fig. 4 Imaging set up for colour reflective imaging. The camera is locked facing vertically downwards. The sample is placed on the copystand over a piece of black card under a sheet of anti-reflective glass. The process of acquiring the images involved manually exchanging each filter in front of the camera lens, causing small movements of the camera each time (which meant the resulting images required further image registration, see Giacometti, 2013)

Table 2 Imaging details per session imaging system and lighting modality, and photograph counts

Session	Modality	Samples	Captures	Number of images
Before degradation	Colour reflective	25	17	425
	Colour transmission	25	17	425
	Monochromatic reflective	25	22	550
	Session total			1,400
After degradation	Colour reflective	25	16	425
	Colour transmission	25	16	425
	Monochromatic reflective	25	21	550
	Session total			1,400
Total				2,800

For each sample, one photograph was taken with each of 16 filters, plus one photograph without a filter.

estimates of the original writing from the degraded samples, and calculate how different our results are from the untreated samples (this is demonstrated in Fig. 6). There is a variety of image processing

methods suitable for this task, including K-means clustering⁹, Principal Components Analysis (PCA)¹⁰, Independent Components Analysis (ICA)¹¹, and Linear Spectral Mixture Analysis

(LSMA)¹², although early on in this research we demonstrated the limited success of K-means clustering for our application (Giacometti, 2013). We therefore processed the multispectral images of each treated sample using three different methods: PCA, ICA, and LSMA¹³.

First, data were cleaned and prepared: each monochrome image was cropped to a square area of 980 × 980 pixels, and the stack of images representing the same sample were co-registered so that each pixel represents the same coordinates on the physical sample. This corrected for movement in the camera as lens filters were changed, and also for some degradation treatments which caused the samples to shrink or curl¹⁴. We used a two-step registration process. An initial linear step preformed gross realignment and a subsequent non-linear step provided non-rigid registration (Giacometti, 2013). Both steps were implemented using software called NiftiReg (Modat *et al.*, 2010). This resulted in a series of images of the treated sample which could be directly compared pixel-by-pixel to images of the untreated sample. The three image analysis procedures were applied to these co-registered images. The output of these consisted of a series of individual images, each of which was intended to show one feature of the sample, for example we might have four images or ‘layers’ representing two inks, a stain, and the underling parchment.

A comparison of the recovered images was then performed. Our aim was to be as objective and quantitative as possible, which was made difficult because the layers obtained from PCA and ICA show degrees of correlation rather than similar intensities. For example, ink might appear as dark on a light background in the sample, but the layer representing ink might appear as a light pattern on a dark background. A straightforward similarity measure such as least squares similarity would give a poor result in this case even if the ink had been perfectly identified. We therefore used an approach known as ‘mutual information’ which is a quantitative measure of the amount of information shared between two images, independent of their colour or intensity (Wells *et al.*, 1996; Panagiotou, 2010)¹⁵. In our case, a successful identification of the text would give a high mutual information score if the patterns

were correctly identified, irrespective of the colour assigned to the recovered layer.

4.5 Controlled damage

We describe three of the twenty methods of destruction in more detail below. These three examples were chosen to illustrate different classes of damage: one where the ink was physically removed (and therefore no longer remains on the document); one where the ink remains in its original form but has been obliterated by a stain; and finally one where the ink remains but has been chemically altered by a bleaching agent.

4.5.1 Scraping

Forcibly removing the surface layer and the visible writing off the parchment with pumice stone¹⁶ was a commonly employed method to re-use parchment (Diringer, 1953; Netz and Noel, 2007), and therefore is a common problem for which multispectral imaging may help in recovering the erased text. We divided our sample into three areas, leaving the top area untreated, the middle area scraped gently, and the bottom area scraped thoroughly for a longer period. The scraping was undertaken by beating a pumice stone until it became powder, and, using a piece of cotton wool, scraping the parchment with this powder, in circular motions.

4.5.2 Blood

Bloodstains are not uncommon in historical documents (Wechsler, 1952), and historical texts can even be written in blood (Gurkina and Rebrikova, 2001; Kieschnick, 2001). Moreover, blood looks similar to iron gall ink, as both haemoglobin and iron gall are rich in the same colour-carrying iron oxides, which contributes to the difficulty of separating ink from bloodstains. In criminology, multispectral imaging has been found of assistance when dating blood stains at crime scenes (Edelman *et al.*, 2012). We stained our parchment with human blood (obtained as expired blood from the UCLH Blood Transfusion Unit), until it fully penetrated the parchment. The excess blood was removed with blotting paper.

4.5.3 Sodium hypochlorite

Sodium hypochlorite is a strong alkaline substance and a common bleaching agent. Reports of experiments with both paper and parchment describe the bleaching effects of both the parchment turning pink and the iron gall ink fading (Smith, 2012). There are also anecdotes of unscrupulous bleaching of parchment by curators and conservators in an attempt to read them (Blagden, 1787; Fuchs, 2003). In our method, 10–15% sodium hypochlorite (NaOCl) was diluted in 40 mL of de-ionised water (pH-5.5) until a pH of 13.0 was reached. This solution was then applied to the parchment.

5 Results

We describe the results of imaging our three methods of destruction in more detail below. We concentrate here on results obtained from monochromatic reflective imaging, as the analysis of these images has produced useful outputs. See Giacometti, 2013 for further research on our other imaging modalities.

5.1 Example 1: Scraping

Figure 5 shows the initial sample, a photograph of the sample after scraping and the best recovered image. The scraping has rendered the affected areas illegible to the naked eye (centre of Fig. 5). There are traces of text remaining on the middle third of the sample, where the scraping was lighter but the bottom third has very few marks where the writing used to be. On the top third, where a single word was removed, there is a darker mark on the parchment, but no traces of the word can be seen. The degradation to the integrity of the parchment is also visible in the samples: the parchment has become physically thinner in the scraped areas.

Figure 6 shows the recovered component images from the sample shown in Fig. 5. The first row of Fig. 6 shows the four largest principal components of the images of the untreated samples. It can be seen that the pattern of the text is recovered successfully, but the intensity is not faithfully recovered—the text is white on black whereas in the original sample (see Fig. 5), it is black on white.

This illustrates the effect described in section 4.4 and the necessity of a technique like mutual information which is sensitive to the overall patterns but not the absolute values to compare the images quantitatively. Each subsequent row displays four registered recovery images resulting from one of the three image processing algorithms (from rows 2–4, PCA, ICA, and LMSA, respectively).

The mutual information between images of the damaged and undamaged samples ranged from zero where there was no information shared between a pair of images to 0.247, which was the highest quantitative similarity and which occurred between NO-PC1 and SC-ICA3 in Fig. 6 above¹⁷.

In this sample, then, the treatment has significantly affected the writing, but there is information that can be recovered using multispectral imaging, and we can visualise some recovery of the writing, while quantitatively indicating the success of ICA to achieve the best results.

5.2 Example 2: Blood

On our sample section shown in Fig. 7, the blood treatment has obscured the writing on the bottom half of the sample. The bloodstains are of a dark brownish colour. The lack of contrast between the stained parchment and the ink renders the writing almost illegible. The treatment has also changed the geometry of the sample, shrinking it slightly. This effect has been corrected in the recovery image by co-registering it with the image of the sample before the treatment shown in Figure 8.

In this case, the affected area of the sample that holds ink is stained, and any interpretation of the sample is difficult on the unprocessed images. The highest mutual information measure was 0.254 and occurred between the unprocessed image and BL-PC2. The mutual information between the unprocessed image and BL-LS3 was almost equally high (0.240).

Our systematic data gathering enables further comparison. We can look at the intensity of each pixel as a function of wavelength (Fig. 9). The top part of Fig. 9 shows the untreated parchment. The band of pixels with high reflectance at all wavelengths corresponds to the background, or the parchment substrate. A smaller, less clustered

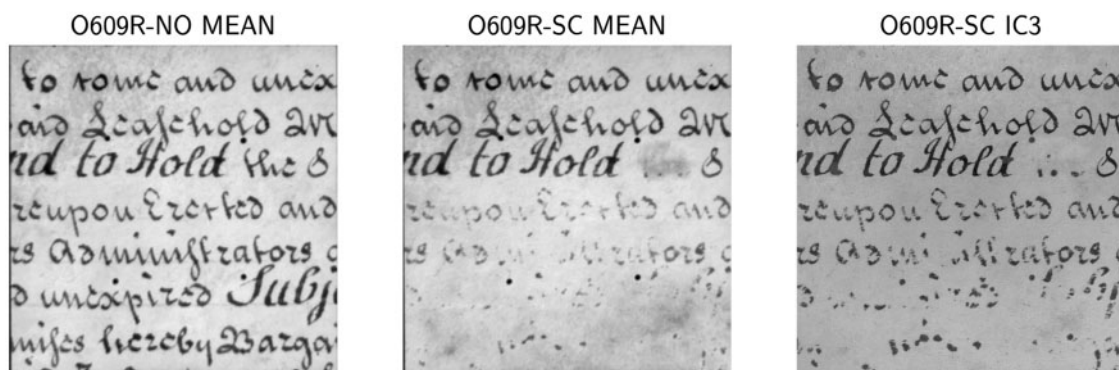


Fig. 5 Sample O609R (left to right) before treatment, after treatment (scraping), and the best possible recovery estimate using our methods (third independent component)

group which corresponds to the writing is darker at shorter wavelengths, but has similar reflectance to the parchment around infrared. However, after the treatment is applied (bottom of Fig. 9), a second band of pixels corresponding to the blood appears and follows a similar path to that of the ink, with the response across the spectrum appearing similar. This demonstrates that the wavelength dependence of blood is similar to that of much of the ink and indicates why the blood makes the ink difficult to read (see also the spectral reconstruction in MacDonald *et al.*, 2013).

In this case, the recovery estimate shows a clear trace of the writing with identifiable letters, even though the image of the treated sample looks, to the human eye, too obscured to be legible. Figure 9 shows that the spectrum of blood is similar to that of ink, so even multispectral imaging might not be completely successful. However, we have shown that PCA is capable of enhancing text, and that PCA is the first image processing method that should be tried when faced with such damage. LMSA also performed well and should be considered if good knowledge of the spectra of the blood and ink are available.

5.3 Example 3. Sodium hypochlorite

The writing on the sample treated with sodium hypochlorite has become very faint (see the bottom part of the central image in Fig. 10). Both the parchment and the writing have become lighter. The areas where the writing has remained visible appear to be where there are stronger ink marks,

suggesting that the ink penetrated deeper into the structure of the parchment. During the application of the treatment, the parchment started to lose structural integrity and some small particles separated from the sample. The treatment was stopped earlier than planned because of this, as the sample needed to be preserved intact for imaging purposes. After drying, the sample became stable again. However, it remained in a fragile state, lighter to the touch, more transparent, smoother, and more flexible than before treatment.

In this case (Fig. 11), the maximum mutual information was 0.294 and occurred for SH-PC1. The second highest occurred for SH-IC4 (0.237). Even the best recovered estimate (right image in Fig. 10) appears to be very similar to the image of the treated sample (middle image of Fig. 10), and our methods have not been able to extract any further information from the text. Multispectral imaging cannot recover text in every example of damage, and our systematic investigations indicate where it is worthwhile using multispectral imaging, and where it simply will not recover any additional information from damaged and deteriorated texts. Our research indicates that text damaged by bleaching agents such as sodium hypochlorite might not generate useful results when imaged multispectrally: this could inform cost analysis on when it may, or may not be, worth imaging particular texts which have indications of this sort of damage.

Further results and discussion regarding all of our degradation techniques, and the results from

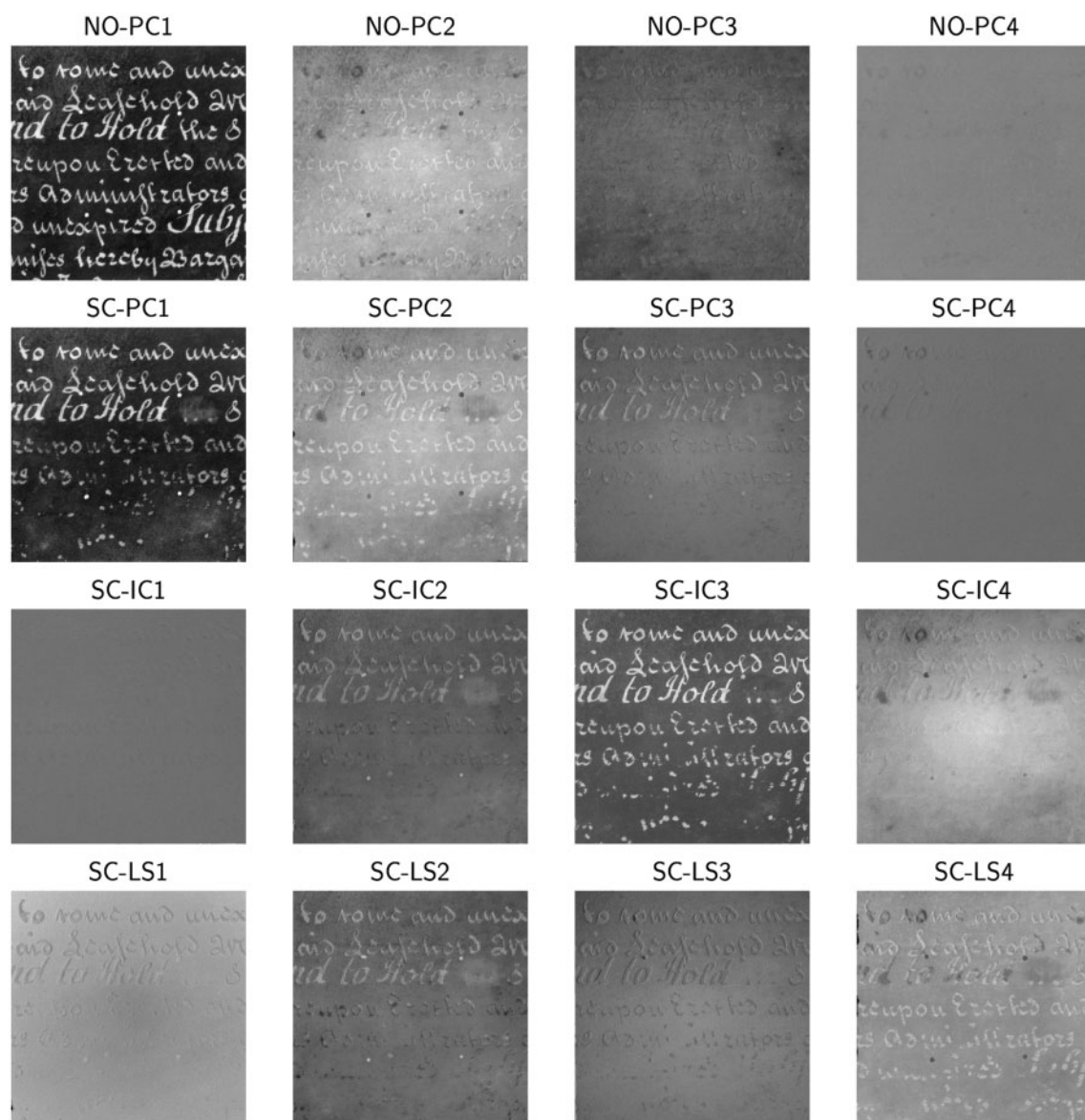


Fig. 6 Sample 0609R (scraping) image processing results by three different processing algorithms. The top row includes PCA of the untreated samples, the next row the PCA of the treated samples. Row three indicates the results further processed with ICA, row four shows LSMA: both are highlighting similarities between the original and the treated samples

both capture and processing are catalogued in Giacometti (2013), providing a framework in which to understand the successes and limitations of multispectral imaging and the image processing algorithms used.

6 Discussion

Our approach—acquiring multispectral images of historical parchment from a set of samples before and after they were submitted to various forms of

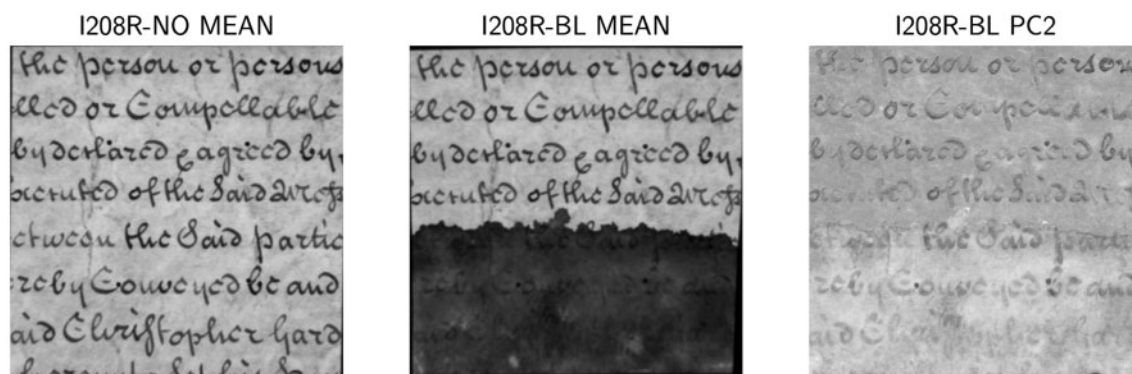


Fig. 7 Sample I208R (left to right) before treatment, after treatment (blood), and the best possible recovery estimate using our methods (second principal component)

degradation—is novel. In this work, we attempted to recover writing from multispectral images, whilst objectively and quantitatively evaluating the effectiveness of image processing algorithms. Our approach successfully identifies the samples which contain more mutual information shared with the original text, and successfully ranks partial recovery of information.

The effect of each of the twenty treatments on both the parchment and the visibility of the writing it carries varied significantly. In some samples in which the writing has been rendered unreadable by the treatment, the writing can be recovered, including aniline dye, oil, and blood. In some samples the writing is completely obscured or the parchment has been severely affected and recovery is all but impossible, including iron gall ink, India ink, and mould. In most cases, however, the image processing algorithms can extract more information from the multispectral images of treated samples corresponding to the writing than the human eye can see.

PCA outperformed ICA and LSMA as the image processing means by which to produce accurate recovery estimates for almost all the samples (although one of our examples shown above, the blood stained fragment, was more successfully recovered with ICA). This shows that there is not one approach or algorithm which suits all types of document degradation, and that the specific condition of a document affects the processing methods which should be used on resulting images. However, PCA is a standard processing algorithm which appears to be accurate and

robust in this application, and is therefore recommended to be used as the first in a range of processes when analysing multispectral images. Further processing may yield improved results.

Our research depends on deliberately degrading square samples cut from a real historical iron gall ink manuscript on parchment. This degradation was necessary to model the type of documentary damage commonly seen in historical documents, and to understand how they affect the reading and interpretation of writing, both before and after multispectral imaging of the samples. The critical destruction is therefore a core part of our method, as it is central to a complete understanding of the effectiveness of multispectral imaging on primary historical texts.

However, our approach does not provide systematic information about any single degradation cause. There is much research to follow on from this, given that we have shown that using carefully prepared historical evidence can provide an effective framework for the evaluation and analysis of the application of multispectral imaging. Additional analysis of our data is possible, and we have already carried our further research into the estimation of spectral signatures of the materials present in the documents from the collected multispectral images (MacDonald *et al.*, 2013). We envisage that the dataset has the potential to become an invaluable asset for libraries and archives, research in conservation, and various problems in image and signal processing, and have made all of the data generated

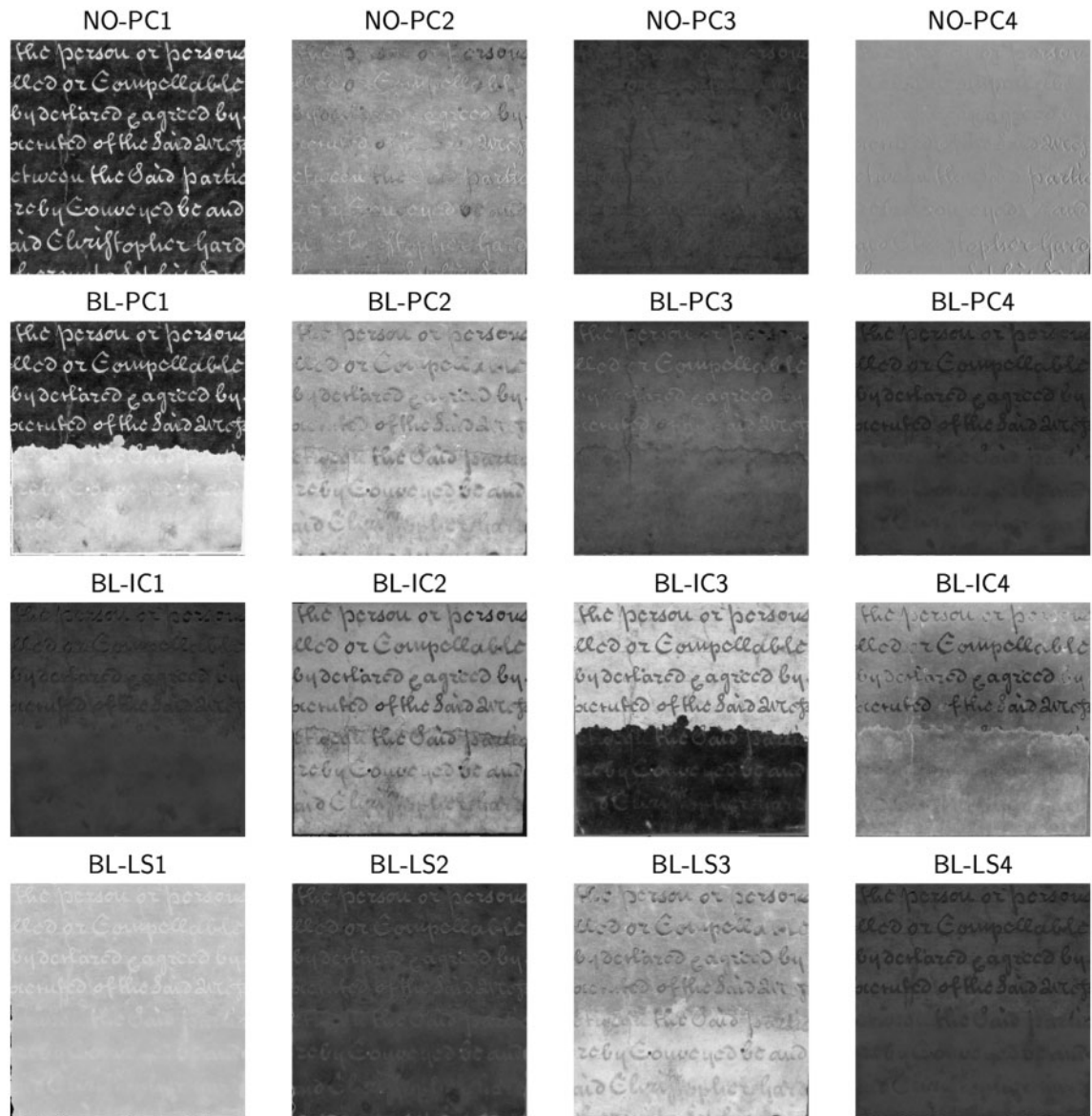


Fig. 8 Sample I208R (blood) image processing results by processing algorithm. The top row includes PCA of the untreated samples, the next row the PCA of the treated samples. Row three indicates the results processed with ICA, row four shows LSMA: both highlight similarities between the original and the treated samples

from this project available for use by others¹⁸. Our dataset provides physical information of how parchment reacts to various forms of degradation, and also provides documentation on acquisition, and will provide a resource for future research (reducing the need for experimentation on valuable primary

historical texts). Our next step will be to carry out a similar process concentrating solely on systematically reproducing different degrees of an individual type of degradation (such as water damage or smoke and heat) to provide further information to help both future conservation and digitisation efforts.

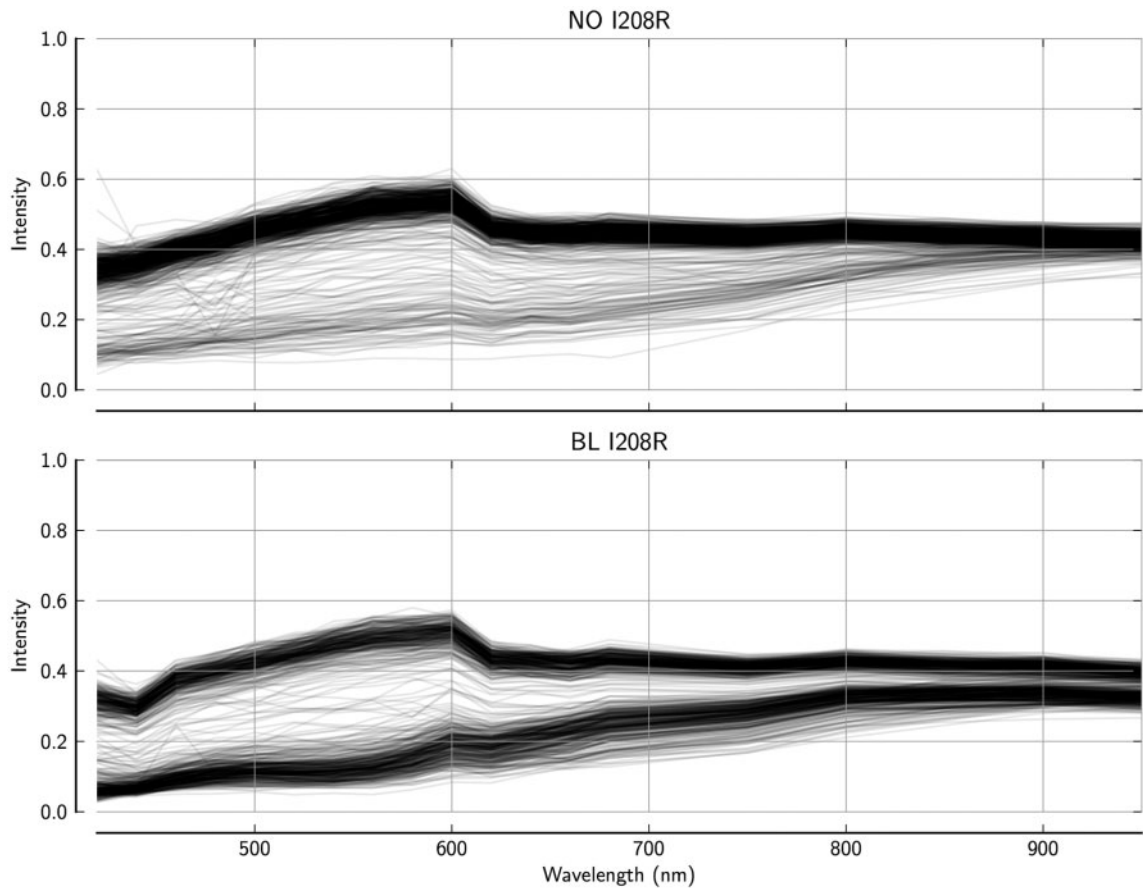


Fig. 9 Sample 1208R (blood) spectral intensity against wavelength. Above: before treatment. Below, after treatment

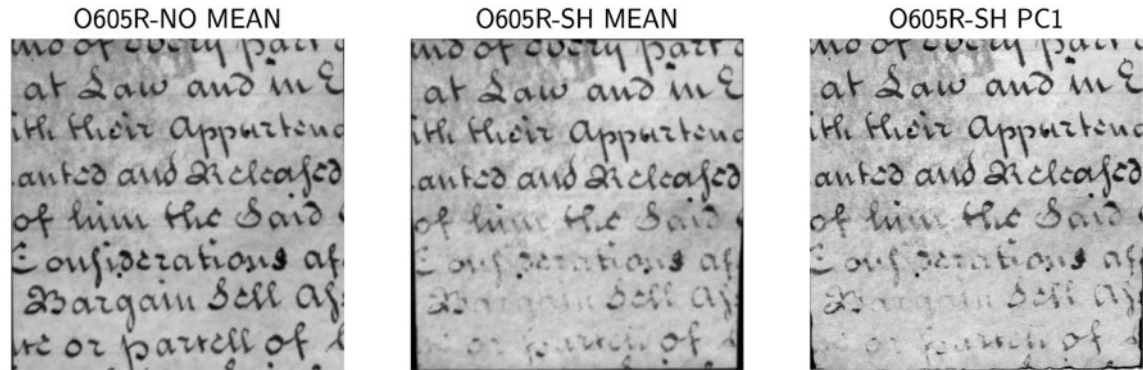


Fig. 10 Sample O605R (left to right) before treatment, after treatment (sodium hypochlorite), and the best possible recovery estimate using our methods (first principal component)

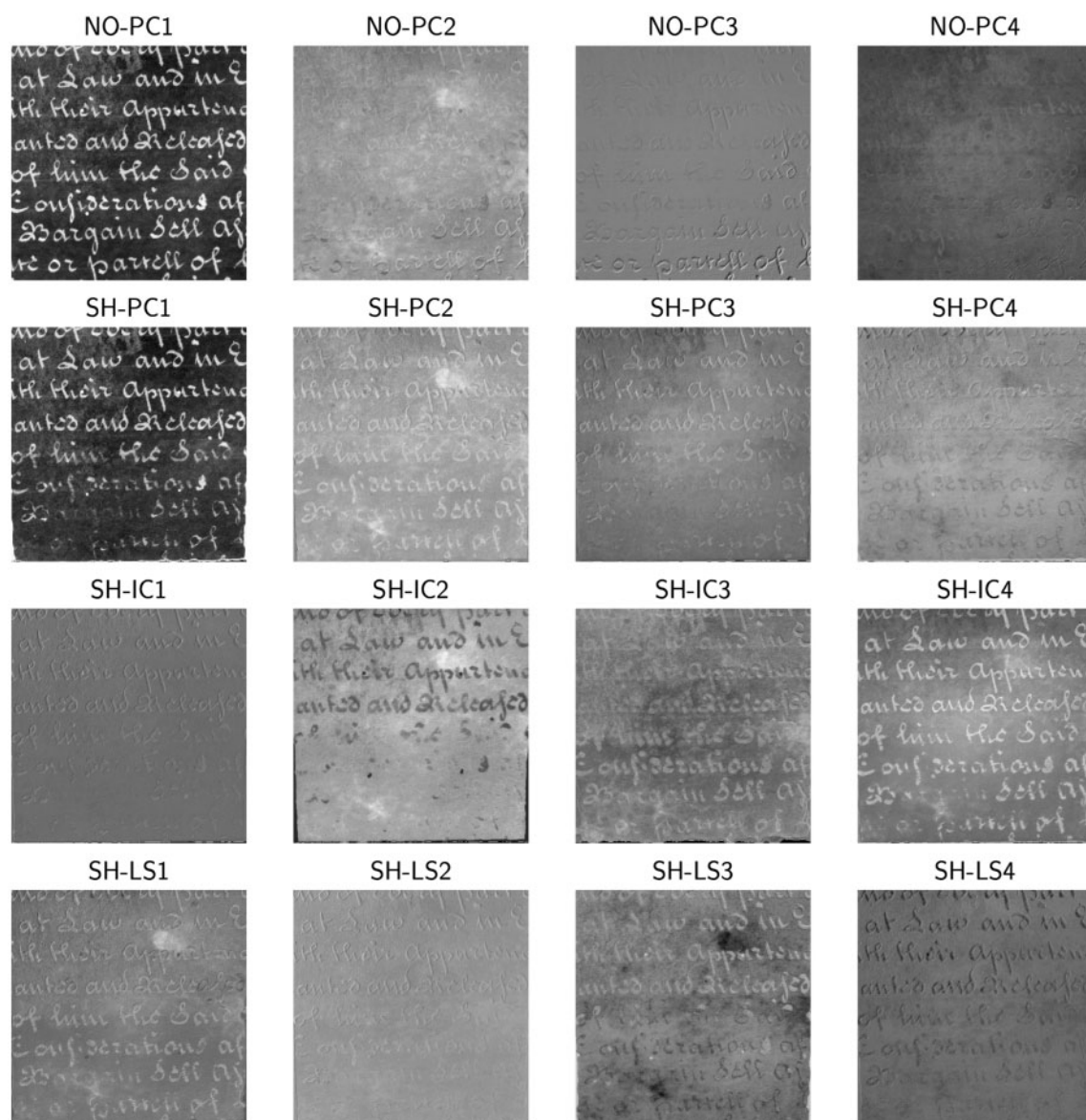


Fig. 11 Sample O605R (sodium hypochlorite) image processing results by processing algorithm. The top row includes PCA of the untreated samples, the next row the PCA of the treated samples. Row three indicates the results further processed with ICA, row four shows LSMA

7 Conclusion

As multispectral imaging becomes more frequently used in the cultural and heritage sectors, it is important to understand the framework which underpins its application to the capture and analysis of

primary historical texts. Our research has provided a systematic methodology for the continuing study and evaluation of the techniques involved in the analysis and processing of multispectral images of degraded cultural heritage documents, and a basis for further testing and development. Understanding

the most efficient way to apply these techniques to damaged and abraded texts is central to ensuring that the images created when using multispectral imaging—which becomes evidence to be used by a range of scholars including historians, palaeographers, and papyrologists—can be trusted by researchers, whilst also making the most efficient use of resources. Our systematic approach provides a framework for the analysis of deteriorated documents using multispectral techniques.

Carrying out this type of interdisciplinary research facilitates a deeper understanding of the artefacts, multispectral imaging, and image processing methods. Specifically, it provides a methodology for the continuing study of the techniques involved in the analysis and processing of multispectral images of degraded cultural heritage documents, and a framework for further testing and development. It has required input from conservators, digitisation specialists, medical physicists, engineers, and computer scientists, archivists all collaborating in a Digital Humanities project where aspects of computing are advanced as much as our understanding of a process that can be useful for humanities scholars. Our unique methodology, where the destruction of a historical text is necessary to acquire experimental data for evaluation, can now be used to evaluate a process for reading other, more valuable, historical texts. Our combined critical approach to a developing technology allows us to advise and steer the application of multispectral techniques to primary historical texts.

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Notes

- 1 An analysis of submissions to the Digital Humanities 2014 conference carried out by Scott Weingart demonstrates that work on text processing remains the core focus of the Digital Humanities community (Weingart, 2013b), with an analysis of DH2014 acceptances indicating that ‘Literary studies, text analysis, and text mining still reign supreme’ (Weingart, 2014). This follows the same trends identified in Weingart’s analysis of Digital Humanities 2013 acceptances (Weingart, 2013a). An earlier analysis of the most used words in the ACH/ALLC Conference abstracts 1996–2005 (Terras, 2006b, p. 236) indicates that text was the focus on this earlier work of the Digital Humanities community.
- 2 At the Digital Humanities conference 2014, one of the eight panels was devoted to image processing (Crowther *et al.*, 2014), and the program also contained a range of short and long papers dealing with image processing, optical character recognition, and the search, retrieval, and navigation of high resolution document image collections (DH2014, 2014).

- 3 Other emerging techniques of interest to those aiming to recover information from primary historical sources include infrared or near-infrared imaging (Workman and Weyer, 2007), and three dimensional imaging such as micro-CT (Baumann *et al.*, 2008), 3D laser scanning (Barnett *et al.*, 2005), and Reflectance Transformation Imaging (RTI) (Earl *et al.*, 2010).
- 4 These are the most popular ways to capture multispectral images in the heritage sector, although the cost of obtaining equipment can still be prohibitive for many institutions to undertake this sort of analysis. At the time of writing, a set of narrowband multispectral filters retails in the region of £10,000 (and will also require additional camera and lighting equipment to be able to be used with it: this is the system we use in this experiment). A full system for production and capture of specific light wavelengths currently retails for £80,000. Camera sensors that can select wavelengths automatically have been developed (Balas *et al.*, 2003), but these are not commercially available. Relatively low cost scanners have been developed that claim full multispectral capabilities, currently retailing for £2,000 (Information in Images, 2014), but these claims have not been verified by independent tests.
- 5 Although there are now over forty different guidelines in existence which detail best practice in straightforward digitisation of cultural and heritage materials (Conway, 2008), none of them has described ideal approaches for the capture, analysis, and storage of multispectral images of heritage material.
- 6 Ratto, 2011; Ramsay and Rockwell, 2012; Schuman, 2014.
- 7 The creation of virtual models, or ‘phantoms’, to allow this comparison is also explored in detail in Giacometti (2013) and Giacometti *et al.*, (2015).
- 8 www.lma.gov.uk
- 9 K-means clustering is a method to separate data points into a number (k) of clusters according to underlying shared characteristics. For example, an image showing parchment and two different inks might be separated into $k=3$ clusters, so that the pixels representing the three ‘layers’ are identified separately. See Hartigan and Wong (1979), Gray and Neuhoﬀ (1998), and Lucchese and Mitray (2001).
- 10 PCA is a technique for decomposing a set of data into its intrinsic variability, preserving the maximum variability of the data in fewer dimensions (Jolliffe, 2002).

In the ideal case, each of the principal components would show one layer from the image.
- 11 ICA is designed to separate sources of signals from a series of measurements (Hyvärinen *et al.*, 2001). Independent components are not ranked, and the energy of each dimension is not preserved, or meaningful. It behaves similarly to PCA but can give different results. Again, we would aim that each of the independent components shows a different layer from the image.
- 12 LSMA decomposes multispectral image data into layers of materials by using *a priori* knowledge of the spectral signals of materials that are present (Heinz and Chang, 2001). This requires knowledge of the absorption spectrum of each dye, which might not always be available.
- 13 Further descriptions of these techniques and applications are available in Chapter 2 of Giacometti (2013).
- 14 Non-linear or non-rigid transformations are those that affect one area of an image in a different way to other areas (Hill *et al.*, 2001), thus allowing compensation when one side of the parchment has shrunk, etc.
- 15 The amount of information in an image can be formally calculated as the *entropy* of the image. A blank image has no information and has entropy = 0, whereas a completely random image carries maximum information (in that the value of one pixel cannot be predicted by that of its neighbours) and therefore has maximum entropy. The information shared between two images can be given as the *joint entropy* which increases as two images differ, because if the images are different, one cannot be used to predict the other. If the entropy H of an image X is $H(X)$ and the joint entropy of images X and Y is $H(X,Y)$, then we can define the *mutual information* $I(X,Y)$ as the information shared between two images, or equivalently their similarity. Then, formally, $I(X,Y) = H(X) + H(Y) - H(X,Y)$.
- 16 The procedure sometimes involved softening the parchment using a mixture of cheese, milk, and lime, before proceeding to scrape the writing using a knife or razor (Diringer, 1953).
- 17 Full data are available in Appendix C of Giacometti (2013).
- 18 The DOI for this dataset is 10.14324/000.ds.1469099
- 19 The figures included in this paper were originally published in Giacometti (2013).